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DETERMINATION OF MECHANICAL PROPERTIES OF ALLOY STEEL 30KH2SH2MFA ACCORDING TO THE INSTRUMENTED INDENTATION RESULTS

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Summary. *The possibility of using the instrumented indentation method in mechanical engineering on the example of steel 30KH2SN2MFA is substantiated. The mechanical properties obtained by the instrumented indentation method are confirmed by the results of uniaxial tension tests. The deviation of the strength properties determined using the instrumented indentation method from the results of tensile tests does not exceed 5%.*
Key words: *instrumented indentation method, tensile test, hardness, microhardness, mechanical properties, tensile strength, yield strength.*

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Introduction. High-strength alloy steels are used in the manufacturing of responsible parts and elements of complex special purpose structures, operating in complex conditions of static loading and short-term dynamic loads, including impulse ones, which have high values. Carrying out the control of mechanical characteristics of such special structures requires the development and evaluation of methods of their mechanical characteristics control. Taking into account the specific features of the production and use of special purpose structures, the application of approved non-destructive testing methods is the priority one, which can be performed using the instrumented indentation.

The investigations carried out in this paper are aimed at the experimental substantiation of the application of the instrumented indentation method in mechanical engineering for the assessment of the current state of materials of special purpose structures for the their efficiency prediction.

Materials, test methods and equipment. The high-strength stainless steel grade 30Kh2SN2MFA used for the of special purpose structures production was selected as the object of investigation.

Tests for niaxial tension were performed according to DSTU EN 10002-1: 2006 [1] at Instron 8802 installation at room temperature. Workpieces for proportional flat samples were cut according to GOST 7564-97 [2] in two orthogonal directions OX and OY from 6 mm thick sheet rolled metal. The samples deformation was measured by automatic registration using strain gauge converter mounted on them. The loading rate was 0.02 mm/min. The mechanical properties characteristics were determined according to [1]. The scheme of workpieces cutting for samples is presented in Fig. 1.

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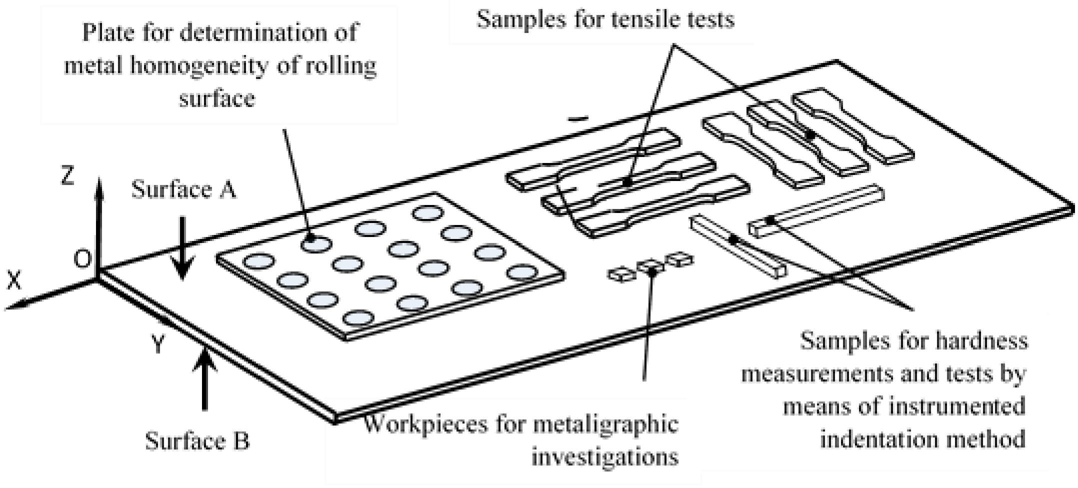


Figure 1. Cutting scheme of workpieces and samples for testing

Samples for testing by instrumented indentation and hardness measurement methods were carried out in three mutually perpendicular directions OX, OY and OZ. Hardness by Brinell method was measured according to DSTU ISO 6506-1: 2007 [3] on the stationary TSH-2 hardness tester. Instrumented indentation was carried out in accordance with the international standard ISO 14577-1: 2015 [4] in the cyclic loading mode with 2.5 mm diameter ball on UTM-20HT laboratory unit [5]. Indentation charts were recorded at constant indenter movement rate 0.05 mm/min. The maximum load was 4000 N. At the same time, all the requirements of the operating documents for the appropriate test equipment were observed.

The characteristics of the mechanical properties of the investigated steel by the method of instrumented indentation were determined according to the methods given in the standard of SOU-56-28-2018 [6], which was developed at GS Pisarenko Institute of Strength Problems of the NAS of Ukraine. Particularly:

- the tensile strength $\sigma_в^{IIT}$ was determined by correlation:

$$\sigma_в^{IIT} = k_{1\sigma в}^{IIT}\,\alpha + k_{2\sigma в}^{IIT}, \qquad (1)$$

where $k_{1\sigma в}^{IIT}$ and $k_{2\sigma в}^{IIT}$ are coefficients determined experimentally and equal to 0.029 and 105.55 for steels, respectively; α is the tangent of the inclination angle of the indentation chart in the coordinates «maximum load F_{max} is the residual depth of indentation h_p after removal of the load»;

- conditional yield strength $\sigma_{0,2}^{IIT}$ was determined by the improved Haggag technique [7]. For the investigated steel, the correlation between the conditional yield strength determined from the uniaxial tensile test data and the parameter A characterizing the material plasticity reserve in the equation, describing the indentation chart in the coordinates «stress in the imprint F/d^2 – deformation d/D»:

$$\sigma_{0,2}^{IIT} = k_{1\sigma 0,2}^{IIT}\,A + k_{2\sigma 0,2}^{IIT}, \qquad (2)$$

where $k_{1\sigma 0,2}^{IIT}$ та $k_{2\sigma 0,2}^{IIT}$ – are determined experimentally coefficients for the investigated steel 30X2CH2MFA equal 0.25 and 0, respectively.

The metal homogeneity was determined by the method of LM-hardness according to DSTU 7793: 2015 [8], the advantage of which is the ability to carry out current control of the technical condition of operating equipment without damaging the structure integrity. The technique is based on the determination of the degree of hardness scattering in its mass measurements, which significantly depends on the degree of the structure uniformity and, as the consequence, on the level of its damage: the smaller the homogeneity, the greater the scattering. The implementation of this method in practice [9, 10] indicates the reasonableness of its application. Homogeneity control was performed with the portable ERNST Computest SC hardness tester on the surface of rectangular plate cut from the investigated steel sheet. The hardness was measured by Brinell HB30 on both sides of the plate in 16 sections that are uniformly located between themselves and relatively to the edges (see Fig. 1).

The chemical composition of the steel metal was analyzed by means of DFS-36 spectrometer at depth of 0.1 – 0.25 mm from the surface.

Metallographic investigations were carried out by optical inverted microscope «AXIOVERT 40 MAT» with microstructure fixation with digital camera SANON A640 in the program «AXIOVISION LE» at magnifications from 100 to 1000. Polished sections were produced on «BUEHLER» installation according to the standard method followed by detection of microstructure by ething in 4% nitric acid in ethyl alcohol. Sample cutting for metallographic investigation was performed in three mutually perpendicular planes – XOY, YOZ and XOZ (see Fig. 1).

Measurement of microhardness $HV_{0.1}$ under 100 g load along the sheet thickness was carried out by microhardnessmeter PMT-3 according to GOST 9450 – 76 [11].

X-ray structural (diffractometric) investigations of steel in order to determine quantitative phase analysis were carried out on DRON-UM1 diffractometer in monochromatic CuKα-radiation by step scanning of the sample surface (U = 35 kV, I = 25 mA, exposure time at the point – 3 seconds, step – 0,05º, output slits – 1x12 mm). Single graphite crystal was used as monochromator. The survey of the diffraction patterns was performed from the rotating sample.

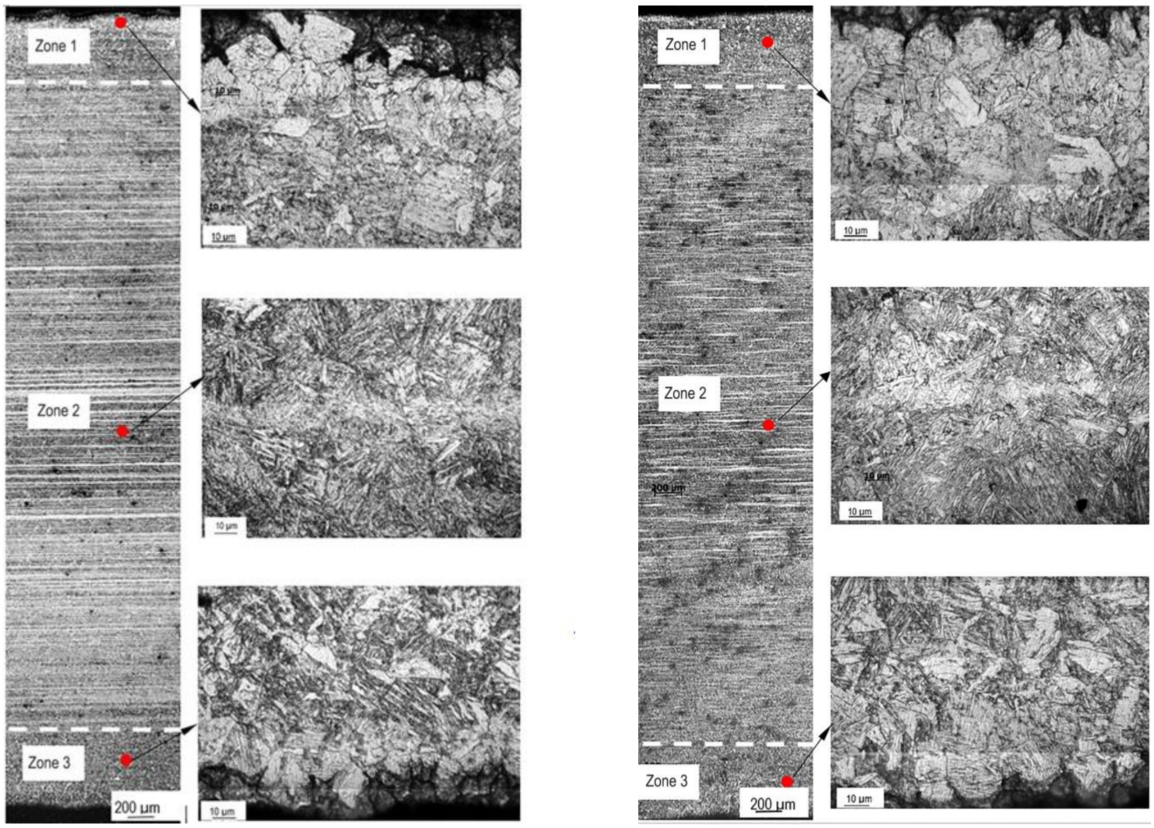
Results of the investigations and their discussion. Analysis of the chemical composition of the investigated steel indicates that less carbon content is observed in the sheet layers at a distance up to 0.5 mm from the surface (zone 1.3 in Fig. 2) compared to the central ones (zone 2 in Fig. 2). This can be explained by the decarburization of the material outer layers caused by technological factors (for example, the rolling peculiarities and servicing), which in turn led to the change in the microstructure and hardness values from the sheet surface to some depth (Fig. 3). The chemical composition of the investigated steel is given in table. 1.

It was revealed during the microstructure investigation that in XOZ and YOZ planes, the macro- and microstructure of steel at some distance from the sheet surface in zone 2 is characterized by dark and light-etched elongated stripes, which density and width varies with the sheet thickness (Fig. 2, a, c) . They are traces of the original rolling texture (texture after rolling up to servicing), but if in YOZ plane the light-etched stripes are continuous, then in the XOZ sheet plane they are discontinuous (interrupted). In addition, larger number of defects (etched micropores) are observed in the XOZ sheet plane in comparison with YOZ plane. The above mentioned structure differences are noticed only at magnifications up to 200 times, but at 500–1000 times magnifications and above in both planes the marked microstructure differences identified as martensite, are not revealed (Fig. 2, b, d).

Table 1

The chemical composition of steel 30Kh2SN2MFA

Data source	*Weight composition of the elements, %*													
	C	*Mn*	*Cr*	*Ni*	*Mo*	*Cu*	*S*	*P*	*Si*	*V*	*Al*	*Ti*	*Ca*	*H2*
Spectrometer	*0,13*	*0,63*	*1,60*	*2,23*	*0,47*	*0,007*	*0,008*	*0,013*	*1,19*	*0,20*	–	–	–	–
DFS-36	*0,29*	*0,64*	*1,63*	*2,14*	*0,48*	*0,05*	*0,001*	*0,009*	*1,29*	*1,87*	*0,028*	*0,018*	*0,00027*	*0,00029*

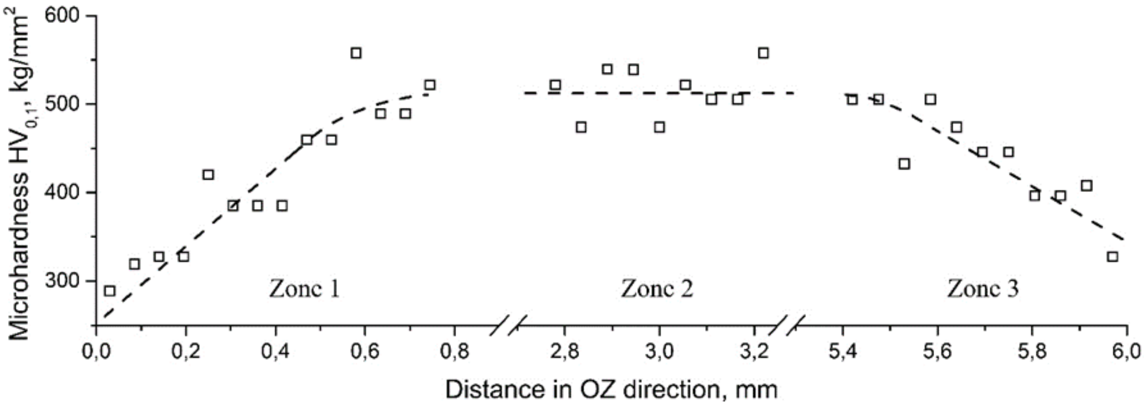


(a) (b) (c) (d)

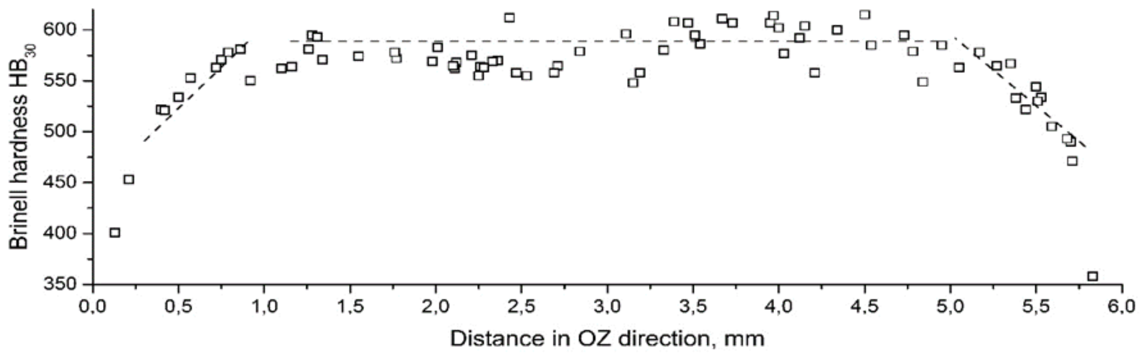
Figure 2. Macro – and microstructure of the investigated steel along the sheet thickness in the XOZ (a, b), YOZ (c, d) planes at various magnifications

As can be seen from Fig. 2, the steel microstructure in the carbonless outer layers of the metal (in zones 1 and 3) contains bainite and martensite, in this case the fraction of the martensitic component increases with the distance from the surface. The residual austenite in the structure is not revealed, and this is confirmed by X-ray structural studies (Fig. 4).

Thus, on the basis of metallographic investigations, the heterogeneity of the microstructure of high-strength steel sheet in thickness was found, which causes the heterogeneity of the microhardness $HV_{0,1}$ (Fig. 3 a), which values vary from 300 kg/mm^2 close to the surface (in zones 1 and 3) to 530 kg/mm^2 in the central area (zone 2). The Brinell hardness distribution along the sheet thickness is also similar, and the change in HB_{30} values reaches 14% (Fig. 3 b).



(a)



(b)

Figure 3. The distribution of the sheet thickness of microhardness according to Vickers $HV_{0.1}$ in OY (a) direction and Brinell hardness HB_{30} in OY (b) directions

The low material heterogeneity degree can be observed on the rolled surface – the Weibull homogeneity coefficient m characterizing the hardness scattering values on the surface does not exceed 25% (Fig. 5)

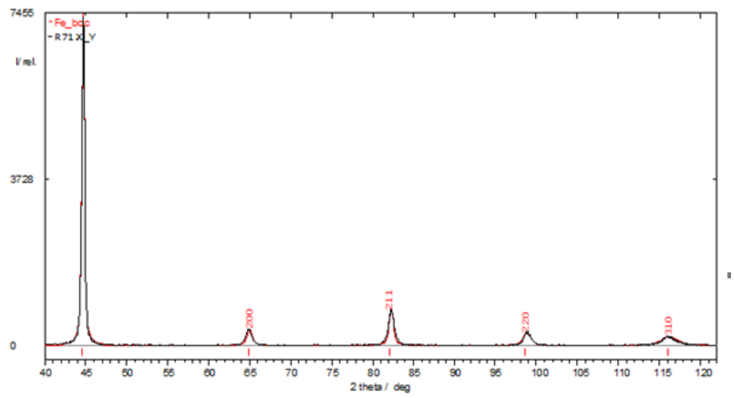


Figure 4. Diffractogram of the investigated steel

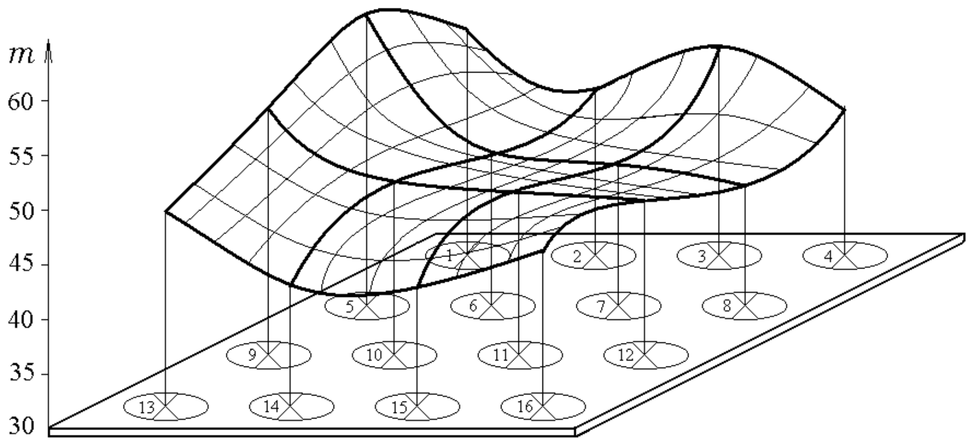


Figure 5. The distribution of homogeneity coefficient m on the steel 30H2CHNMFA sheet surface

The hardness values according to Brinell HBW (according to [3]) of the investigated material, obtained by averaging the results of ten measurements on the samples sheet surfaces in directions OX, OY and OZ (surfaces A and B) are given in Table 2.

Table 2

The results of alloyed steel 30X2CH2MFA.hardness determination according to Brinell

Direction of hardness determination	Hardness according to Brinell, HBW
OX	503
OY	543
OZ (surfaces A)	418
OZ (surfaces Б)	424

It is evident from the data given in table 2, that the hardness values of 30Kh2SN2MFA steel according to Brinell, defined in the directions of the sheets cross sections OX and OY are higher than on the surfaces A and B up to 25%.

Diagrams of static tension of proportional flat samples made of the investigated material in directions OX and OY are shown in Fig. 6.

Mechanical characteristics of steel 30Kh2SN2MFA, determined from uniaxial tension in directions OX and OY are given below: direction OX – E = 1,99×105 MPa, $\sigma_{0,2}$ = 1323,7 MPa, $\sigma_в$ = 1691,0 MPa, δ = 7,2%. direction OY – E = 2,03×105 MPa, $\sigma_{0,2}$ = 1308,0 MPa, $\sigma_в$ = 1717,7 MPa, δ = 10,5%. Deviation of the values of the steel mechanical properties characteristics in direction OX from the values determined in direction OY is 1,6% for $\sigma_{0,2}$, 2,5% for $\sigma_в$ and 31,4% for δ.

Cyclic diagrams of the steel instrumented indentation in directions OX, OY and OZ are shown in Fig. 7.

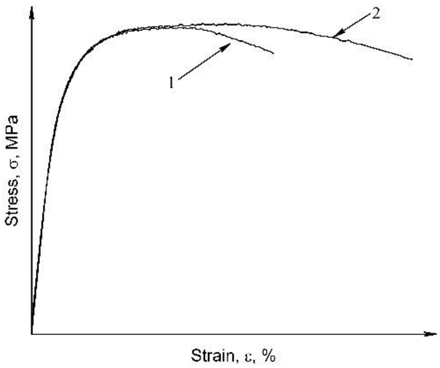


Figure 6. Static tension diagrams of proportional flat samples from steel 30Kh2SN2MFA along the directions OX (1) and OY (2)

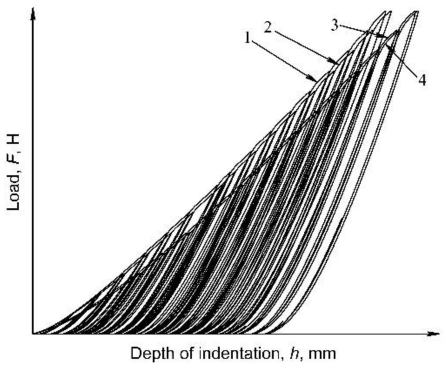


Figure 7. Cyclic diagrams of instrumented indentation of steel 30Kh2SN2MFA in directions OY (1), OX (2) and OZ on surfaces B (3) and A (4)

The values of the conditional yield strength $\sigma_{0,2}$ and the tensile strength boundaries $\sigma_в$ of 30Kh2SN2MFA steel determined by the instrumented indentation method, as well as their deviations from those obtained by the uniaxial tensile test results, are presented in Table. 3.

Table 3

Mechanical properties of steel 30X2CH2MFA determined by the instrumented indentation method and their deviations

Direction of mechanical characteristic determination	Yielding boundary $\sigma_{0,2}$, МПа	Deviation, %	Srength boundary $\sigma_в$, МПа	Deviation, %
OX	1295,4	2,2	1627,6	3,7
OY	1305,2	0,2	1668,0	2,9
OZ (surface A)	1337,0	–	1489,5	–
OZ (surface Б)	1322,8	–	1491,1	–

It is evident from the table. 3 that the deviation of mechanical characteristic values determined by instrumented indentation method from the same one while tensile does not exceed 5%. In this case the deviation of mechanical characteristic values determined on the rolled metal surfaces A and B from that obtained in directions OX and OY is up to 3.2% $\sigma_{0,2}$ and 12% for $\sigma_в$. The obtained results indicate the appropriateness of the instrumented indentation method for determining the mechanical characteristics of this class of steels.

Conclusions. As the result of experimental investigations the value of mechanical properties characteristics in three orthogonal directions of thick sheet metal of 30Kh2SN2MFA alloy steel with thickness 6 mm was determined by the instrumented indentation method. It is defined that the deviations of mechanical characteristics values determined on the rolling surfaces A and B from those obtained in directions OX and OY are up to 3.2% $\sigma_{0,2}$ and 12% for $\sigma_в$. The decrease in the values of NV microhardness, NV hardness and the tensile strength determined by the instrumental indentation method in the surface layers of rolled metal (surfaces A and B) is caused by their decarburization and, respectively, by different microstructure compared to the central zone detected on the basis of chemical and metallographic analysis.

As the result of the carried out investigations, microstructural and micromechanical heterogeneity in the material layer were determined to the depth up to 0.5 ÷ 1.0 mm from the sheet surface.

The possibility of using the instrumented indentation method for express estimation of the investigated steel strength characteristics is shown.

The mechanical properties results obtained by the are confirmed by the uniaxial tensile test results. The deviation of the strength characteristics values determined using the instrumented indentation method, from the tensile test results does not exceed 5%. Further application of the instrumented indentation method for the express evaluation of the strength characteristics of materials of such class requires additional investigation.

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ВИЗНАЧЕННЯ ХАРАКТЕРИСТИК МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ЛЕГОВАНОЇ СТАЛІ 30Х2СН2МФА ЗА РЕЗУЛЬТАТАМИ ІНСТРУМЕНТОВАНОГО ІНДЕНТУВАННЯ

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Резюме. *Проведено комплексні дослідження механічних властивостей легованої високоміцної сталі 30Х2СН2МФА з використанням методики інструментованого індентування. З листової заготовки було виготовлено партії зразків у різних напрямках для проведення металографічних досліджень, випробувань на одновісний розтяг, інструментоване індентування та твердість. Випробування проведено на сучасному експериментальному обладнанні з використанням сучасних методик та нормативних документів. Для досліджуваного матеріалу отримано значення твердості за Брінеллем шляхом осереднення результатів десяти вимірювань на поверхнях зразків у трьох напрямках. Проведено співставлення значень умовної границі текучості* $\sigma_{0,2}$ *та границі міцності* $\sigma_в$ *сталі 30Х2СН2МФА, отриманих методом інструментованого індентування та за результатами випробувань на одновісний розтяг. Відхилення в отриманих результатах не перевищує 5%. При цьому відхилення значень механічних характеристик, визначених у двох взаємно перпендикулярних напрямках складає до 3,2%* $\sigma_{0,2}$ *і 12% для* $\sigma_в$*. Зменшення значень мікротвердості HV, твердості HB та границі міцності, визначеної методом інструментального індентування, в поверхневих шарах прокату зумовлене їх зневуглецюванням та відповідно іншою мікроструктурою в порівнянні з центральною зоною, що було виявлено на основі хімічного та металографічного аналізу. Отримані результати свідчать про придатність методу інструментованого індентування до визначення механічних характеристик подібного класу сталей та можуть бути використані при чисельному моделюванні відповідальних деталей та елементів складних конструкцій спеціального призначення для прогнозування їх працездатності.*

Ключові слова: *метод інструментованого індентування, випробування на розтяг, твердість, мікротвердість, хактеристики механічних властивостей, границя міцності, границя текучості.*

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